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Director of Research

CALIBRATION OF FOG WATER COLLECTION AND DETECTION EQUIPMENT AT THE NRC LOW TEMPERATURE LABORATORY

Helen Leung
Engineer
Environmental Science Section
Chemical Research Department

ABSTRACT

The fog water collection and detection equipment used by the Environmental Science Section was tested at the NRC Icing Wind Tunnel and Cold Chamber. The equipment consists of one Forward Scattering Spectrometer Probe, two Fog Measuring Devices, one Optical Cloud Detector and one Fog Water Collector. This equipment was compared with NRC's rotating cylinder technique and AES's Forward Scattering Spectrometer Probe. In general, the equipment correlated well with each other. The Forward Scattering Spectrometer Probe underestimated the liquid water content by about 30% when compared with the rotating cylinder. The response of the Fog Measuring Devices was linear up to a liquid water content of about 1.0 g/m^3 and became saturated at about 2.0 g/m^3. The sensitivity of the Optical Cloud Detector was about 0.05-0.07 g/m^3 at the high sensitivity setting and about 0.12 g/m^3 at the low sensitivity setting. The collection efficiency of the Fog Water Collector was high (>about 80%) at above zero temperature and was low (about 20%) under subzero temperature.

job	file	date	report no.
35-514-033	811.3	August 15, 1990	90-197-K

1.0 INTRODUCTION

This report describes the calibration of the fog water collection and detection equipment used by the Environmental Science Section (ESS). The calibration was carried out at the Low Temperature Laboratory (Icing Wind Tunnel and Cold Chamber) of the National Research Council (NRC) in Ottawa from October 23 to November 3, 1989. The equipment consists of one Forward Scattering Spectrometer Probe (FSSP1), two Fog Measuring Devices (FMD), one Optical Cloud Detector (OCD) and one Fog Water Collector (FWC). These devices are used primarily in the Insulator Icing Study to measure fog droplet size and liquid water content (LWC), and to collect fog water samples for chemical analysis. The information being collected will be used to assess the importance of fog water accretion in insulator flashovers. The FSSP1 is also used in the Water Aerosol Leakage Experiment to study water aerosol formation and behaviour following a hypothesized Loss Of Coolant Accident, LOCA, in Nuclear Generating Stations.

The calibration standard used for LWC in this study was NRC's rotating cylinder method, which requires supporting measurements of droplet velocity and size. These measurements were provided by ESS's velocity meter and by the FSSP1, respectively. Unfortunately, the FSSP1 could not be used throughout the entire study, since it was needed for other work. Instead, an FSSP owned by Atmospheric Environment Service of Environment Canada (FSSP2) was used to provide the droplet size and LWC measurements for the remainder of the study.

The specific tasks that were performed at NRC were divided into two groups:

1) Icing Wind Tunnel Tests

   - To calibrate the FSSP1 with the rotating cylinder
   - To calibrate the two FMDs with the rotating cylinder and with the FSSP2
   - To measure the sensitivity of the OCD with the FSSP2
   - To compare ESS's velocity meter with NRC's Kurtz mini-anemometer.

2) Cold Chamber Tests

- To study the performance of the fog water collector
- To study the performance of the fog water collection and detection equipment

A brief description of the equipment and the results of the calibrations are presented in this report.

2.0 BACKGROUND ON EQUIPMENT

This section describes the operating principles behind the equipment and the accuracy of LWC measurements. This information will be helpful in understanding the calibrations performed in this project.

2.1 Rotating Cylinder

A single rotating cylinder method was used to determine the liquid water content. It was designed and constructed by NRC/1/. The liquid water content can be calculated from the known weight of ice accreted on the rotating cylinder during a specified period of time and from the theoretically derived collection efficiency. The errors introduced in the LWC estimation are about 5% under high wind speed (> about 50 m/s) conditions/1/. The errors in the present test conditions (low wind speed, < about 10 m/s) are uncertain, but were found to be very sensitive to the wind speed and the droplet size used in the calculation. In this study, the median volume dia-meter (MVD) was obtained from the FSSP size spectrum (Section 2.2) and wind speed was taken from ESS's velocity meter (Section 3.4).

2.2 Forward Scattering Spectrometer Probe

The Particle Measuring Systems FSSP (model FSSP-100) uses the forward scattered light from a laser source (He-Ne) to size and count droplets passing through its sample volume. The FSSP1 measures droplet size from 1 to 95 μm over four overlapping ranges. The size resolution is typically 1 μm. The LWC can be obtained by integrating the size spectrum. The LWCs were corrected for the coincidence/dead time loss by two methods: the first method is based on the statistical technique of Baumgardner et al/2/, and the second one is based on the probe activity. In this report, uncorrected LWC corresponds to the LWC uncorrected for coincidence/dead time loss; corrected LWC1 refers to the values obtained by the first method of correction; corrected LWC2 refers

to the values obtained by the second method of correction. The errors in the corrected LWC estimations are about 30-40%/3/. A more detailed description of the FSSP was given in a previous report/4/.

2.3 Fog Measuring Device

The Advanced Electronic Sub-Systems FMD (model FMD-04) is based on the light scattering technique by Gerber/5/, in which a single circular light detector is placed coaxial and perpendicular to a narrow collimated visible light beam. The near-forward scattered light flux is found to vary linearly with the LWC, almost independent of the size distribution of the droplets (< about 28 μm). A prototype based on this method was designed by Advanced Electronic Sub-Systems and field tested by AES's Cloud Physics Division and by ESS. The instrument was found to be very sensitive to the LWC and suitable for low LWC measurements. An improved version, based on a laser source instead of a visible light source, was calibrated in this study. The FMD is different from the FSSP in two aspects. First, the FMD uses a multiple particle counting techniques, whereas the FSSP is based on single particle counting technique. Second, the FMD does not provide droplet size spectrum information but the FSSP does.

2.4 Optical Cloud Detector

The Associated Weather Services OCD (Model FSA-05) determines the presence of droplets optically. The detector depends on near-forward scattering and diffraction of infrared light by droplets. The source and the photoelectric sensor are in-line and intercepted at their centre by a blocker post. Normally the infrared signal is blocked by the post and will not be detected by the sensor. But when droplets exist, they will scatter the light around the post into the sensor. An on/off signal will be generated by a controlled switch, where "on" corresponds to droplets being present and the LED on the sensor will be on. The sensitivity is about 0.045 to 0.06 g/m^3 LWC. The detector has been used to detect the presence of fog on highways in California. The performance of the detector has not been tested under subzero temperature. The detector is used to turn on the FWC used in the Insulator Icing Study.

2.5 Fog Water Collector

The active FWC is a modified version of the California Institute of Technology's strand collector/6/. The fog water is collected by inertial impaction of fog droplets on a collecting screen. The

screen is made up of two layers of 0.53 mm diameter Teflon strings inclined at about 35 degrees in a 25 cm x 25 cm square duct. The ambient fog water-laden air is drawn through the duct by a blower at a velocity of about 7 m/s, which corresponds to a flowrate of about 27 m^3/min. The droplets are then collected through a funnel down to a collection bottle underneath. The collection efficiency of the screen depends on the droplet size and velocity. The efficiency is about 90% for 10 µm droplets at 7 m/s/6/. The collection efficiency increases with the number of screens used. The collector is designed to accommodate up to three collecting screens. In this study, two or three screens were used. The OCD mentioned in Section 2.4 is used to turn on the blower in the FWC.

3.0 ICING WIND TUNNEL TESTS

The FSSP, the FMDs, the OCD and the velocity meter were tested in the Icing Wind Tunnel (Figures 1 & 2). The normal working section of the tunnel is about 57 cm high, 57 cm wide and 183 cm long. The tunnel has a capacity to provide air velocity up to 90 m/s and air temperature from about -35°C to ambient temperature (about 25°C), and is well suited for high velocity work. In this study, however, the air velocity was kept below about 10 m/s. In some instances, the tunnel conditions were not very stable especially under low velocity and high LWC conditions. Air temperature varied from -5°C to about ambient temperature. The water droplets were generated using spraying nozzles. The MVD of the droplets were from about 8.0 to about 15.0 µm. The MVD, in general, increased with the LWC.

3.1 Forward Scattering Spectrometer Probe

A single spraying nozzle was used to generate water droplets. The spraying nozzle, rotating cylinder and FSSP1 (fitted with aspiration horn) were positioned at the main axis of the tunnel (Figure 3). The rotating cylinder measurements were taken within a few minutes before or after the FSSP1 measurements to ensure that they did not interfere with one another. At least two rotating cylinder measurements and six FSSP1 30-s measurements were taken for each operating condition. Range 1 was selected for the FSSP1 that covered the size range from 2 to 47 µm. Furthermore, the honeycomb (the flow straightener for the FSSP1) was not used to avoid icing of the FSSP sample volume. In this part of the study, the LWC varied from about 0.1 to 0.8 g/m^3; the MVD remained about 13 µm; ambient temperature was either at about -2.6°C or -5.7°C.

The results are presented in Table 1. The rotating cylinder measurements varied by 10% except in one case where LWC was low (probably due to the small quantity of ice accreted). In this case,

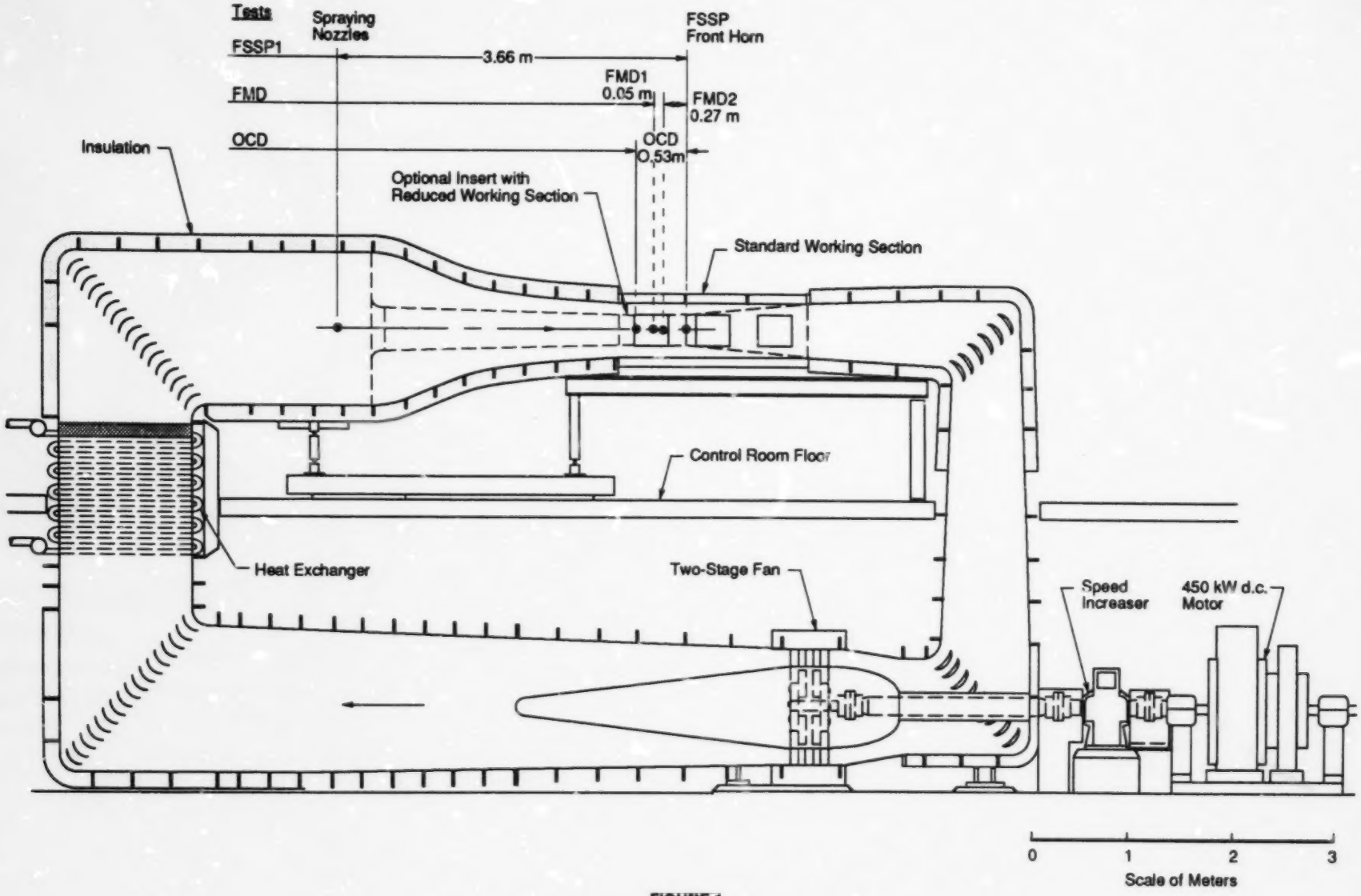

FIGURE 1

EQUIPMENT SET-UP IN THE ICING WIND TUNNEL

FIGURE 2

ICING WIND TUNNEL TESTS

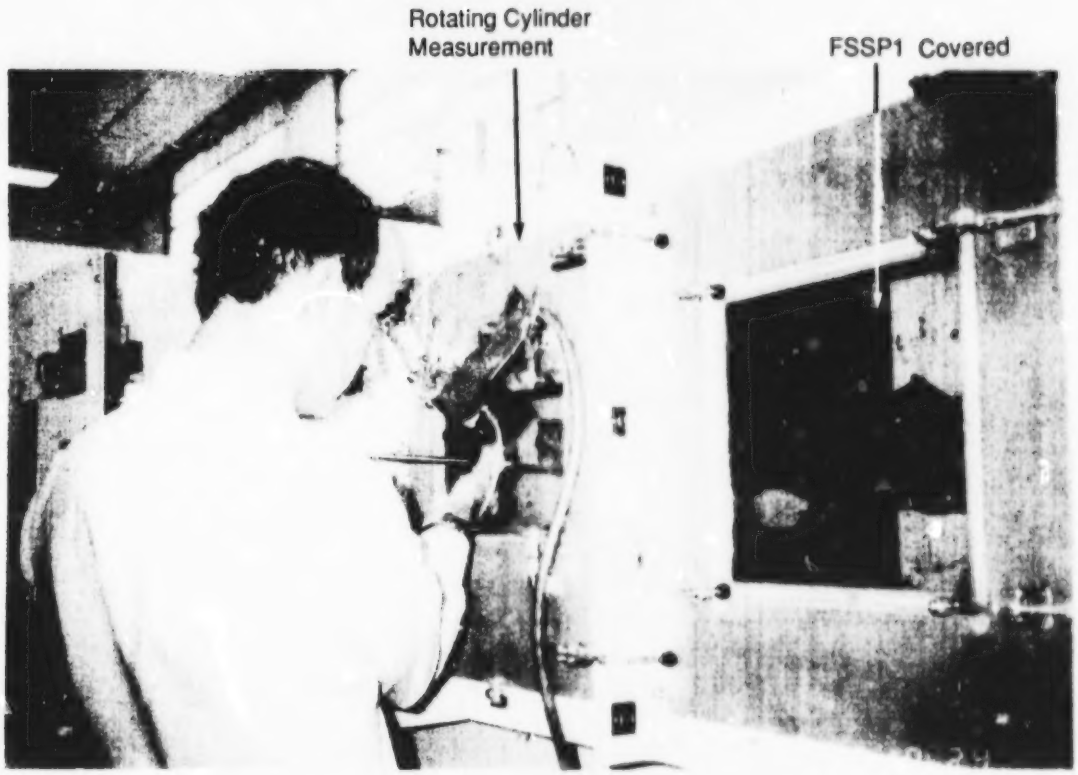

FIGURE 3

FFSP1 CALIBRATION IN THE ICING WIND TUNNEL

TABLE 1

FSSP1 CALIBRATION IN THE ICING WIND TUNNEL

Temp. (°C)	Velocity (m/s)	LWC (g/m^3) Rot. Cylinder @13 µm	FSSP1 Uncorr.	FSSP1 Corr1.	FSSP1 Corr2.
-2.9	2.3	0.22±0.01	0.09±0.01	0.10±0.01	0.10±0.01
-2.5	4.5	0.64±0.04	0.28±0.01	0.41±0.01	0.42±0.01
-2.5	7.1	0.76±0.00	0.33±0.03	0.50±0.06	0.52±0.05
-2.5	10.2	0.81±0.08	0.32±0.07	0.50±0.16	0.51±0.12
-5.9	2.1	0.16±0.06	0.09±0.00	0.09±0.00	0.09±0.00
-5.6	4.4	0.61±0.04	0.33±0.01	0.55±0.04	0.48±0.02
-5.6	10.0	0.77±0.01	0.36±0.08	0.51±0.14	0.56±0.13

the variation was about 35%. Similarly, the LWC determined with the FSSP1, varied by about 10% except in one case where the LWC was high (probably due to high coincidence losses). In this particular case, the variation was about 30%. The corrected LWC1 was very close to the corrected LWC2. A typical size spectrum is given in Figure 4. The MVD was about 13 µm (±2%). The LWC given by the rotating cylinder is plotted against the LWC obtained by the FSSP1 in Figures 5,6 and 7, which correspond to the FSSP1's uncorrected LWC, the corrected LWC1 and the corrected LWC2 results, respectively. A linear relationship exists between the LWC obtained with the rotating cylinder and that from the FSSP1 for LWC up to about 0.8 g/m^3. The coefficient of correlation was better than 0.9. The FSSP1, when corrected for coincidence/dead time loss, underestimated the LWC by about 30% when compared with the rotating cylinder. The observed error is of the same order of magnitude as the errors reported in the literature/3/.

3.2 Fog Measuring Device

The two FMDs were calibrated against the rotating cylinder under subzero temperature and against AES's FSSP2 at above zero temperature, in the wind tunnel (Figure 8). A spraying bar consisting of two spraying nozzles, was used to provide more uniform LWC across the tunnel (instead of a single spraying nozzle). The uniformity was confirmed by observing the pattern of ice deposited on a black painted metal grid inserted across the tunnel. The two FMDs and the

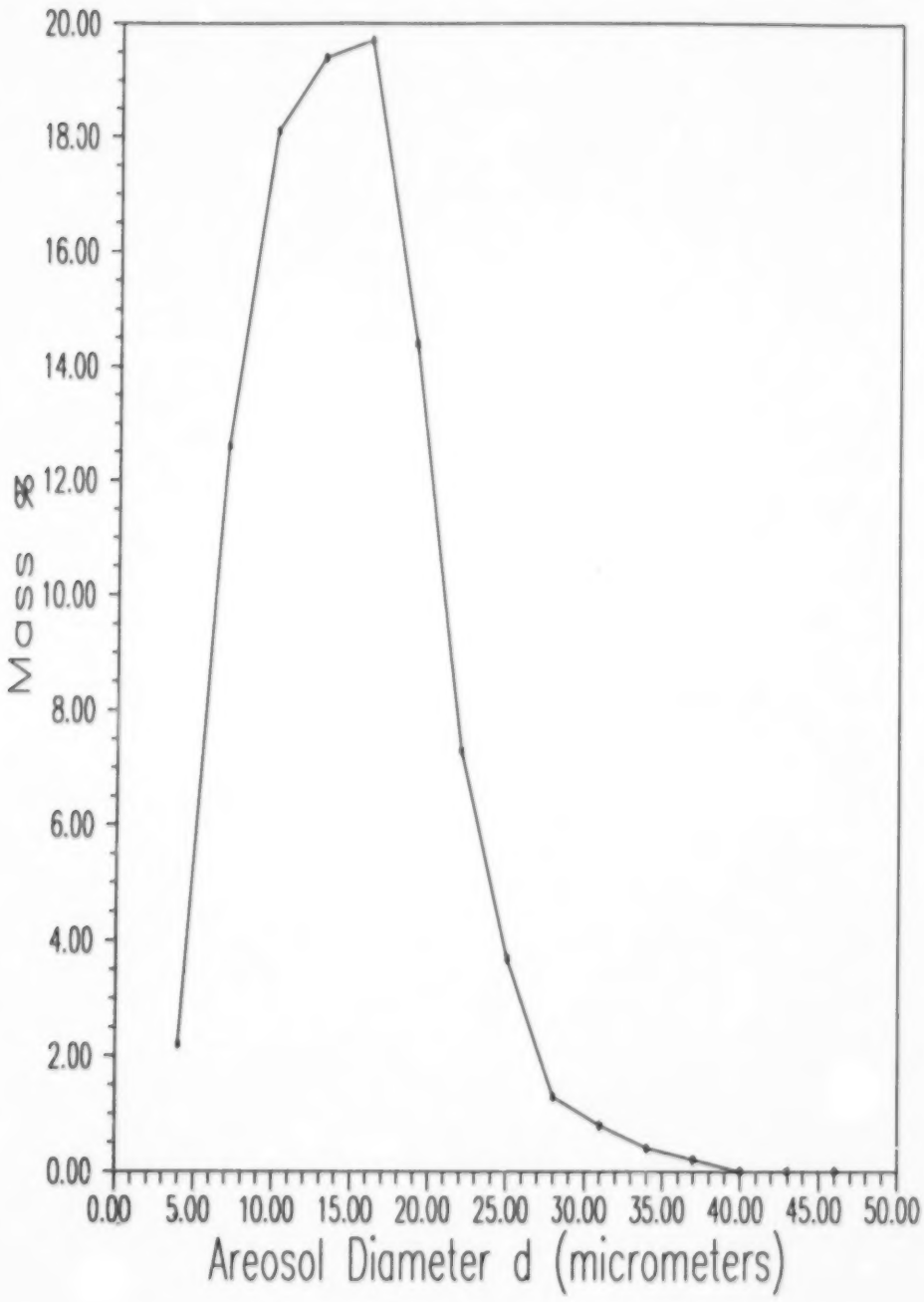

Figure 4 - Typical FSSP's Size Spectrum (NRC, Oct 25, 1989)

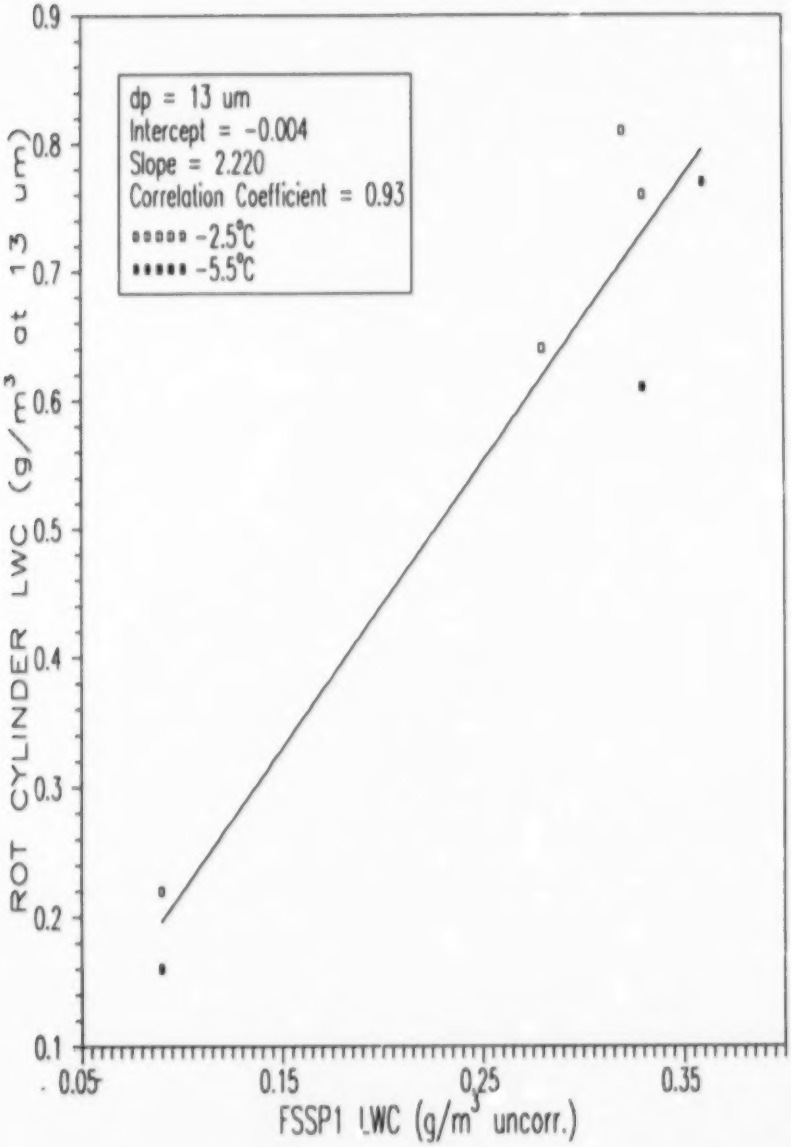

Figure 5 - FSSP1 Calibration (NRC, Oct 25, 1989)

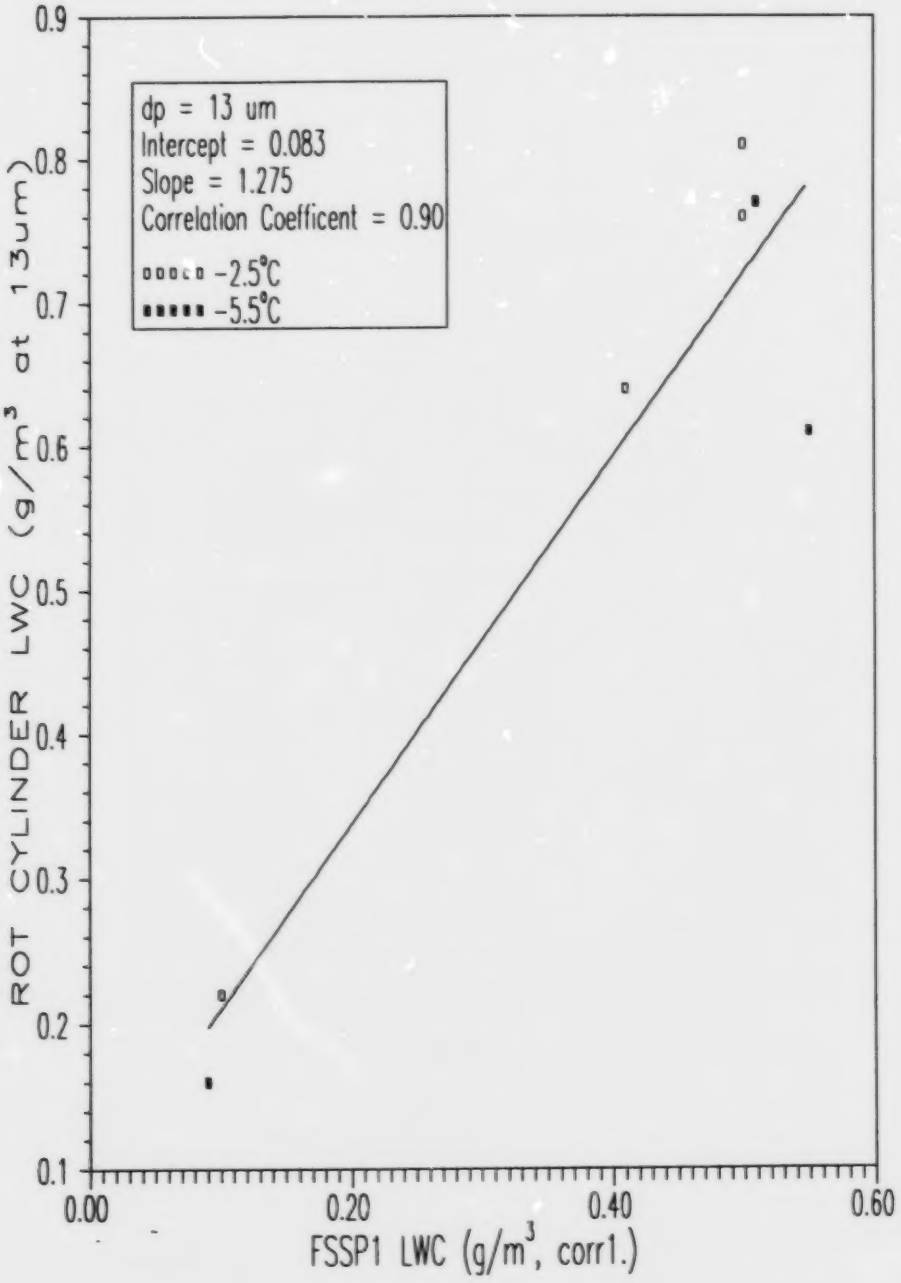

Figure 6 - FSSP1 Calibration (NRC, Oct 25, 1989)

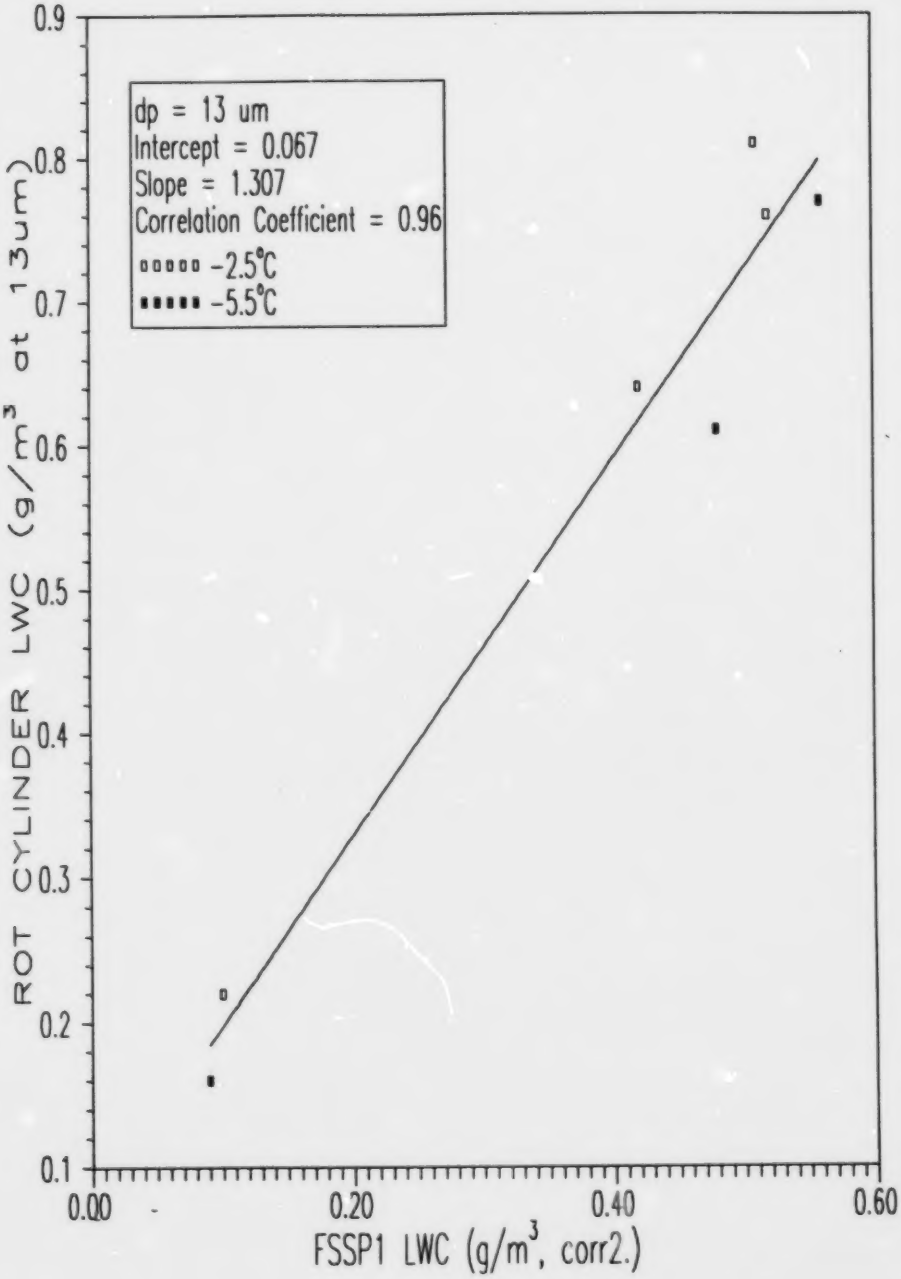

Figure 7 - FSSP1 Calibration (NRC, October 25, 1989)

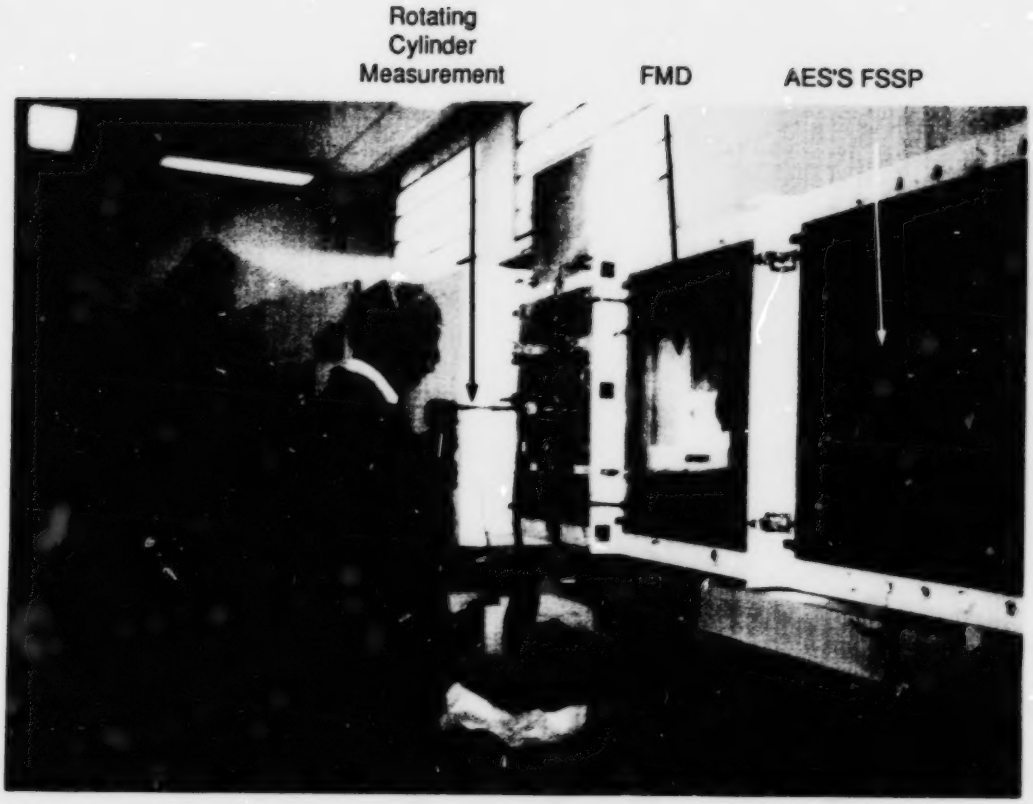

FIGURE 8

**FOG MEASURING DEVICE CALIBRATION
IN THE ICING WIND TUNNEL**

FSSP2 were aligned with the spraying bar. The FSSP2 measurements did not seem to affect the FMD readings. Rotating cylinder measurements were taken at two locations, under subzero temperature: at the front of FMD1, and between FMD1 and FMD2. The two measurements were very close at low LWC and different at high LWC. The tunnel was operated at 4.5 m/s under subzero temperatures and at 2.5 and 4.5 m/s at above zero temperatures. The MVD, determined by FSSP2, changed from about 9 to 28 μm. The LWC varied from about 0.1 to 0.8 g/m^3 under subzero temperatures and from about 0.1 to 2 g/m^3 at above zero temperature. The high LWC was associated with high MVD.

The baseline on the FMDs was found to depend on temperature (Table 2). Fortunately, the baseline varied only slightly in the temperature range of interest in the Insulator Icing Study (between -5 to about 5°C). Once equilibrium was reached (about an hour at an average rate of about 4-5 mV/min), the baseline was quite stable.

The FMD results are given in Table 3. The FMD1 readings, corrected for the baseline drift, are plotted against the LWC taken with the rotating cylinder in front of FMD1 in Figure 9. Similarly, the FMD2 signals are correlated with the LWC taken with the rotating cylinder between FMD1 and FMD2 in Figure 10. Figures 9 and 10 show that the temperature effect was insignificant at -5 and -2.3°C. A linear regression was applied to all the data. The FMD signals were found to vary linearly with LWC (as determined with the rotating cylinder), up to about 0.8 g/m^3. The FMD readings are also plotted against the LWC, measured with FSSP2, in Figures 11 and 12. Again, the temperature effect was insignificant in the range from -5 to about 5°C. The FMD output was found to increase linearly with the LWC (as determined with FSSP2), up to about 1.0 g/m^3 and to become saturated at high LWC (about 2 g/m^3). The effect of wind speed on the FMD response was insignificant at low LWC (up to about 1 g/m^3). At high LWC, the FMD output at saturation was slightly different at 4.5 and 2.5 m/s. This effect was unknown and may be due to the large droplets used in the high LWC tests, the unstable tunnel condition at low wind speed and high LWC, or the behaviour of the FSSP2. Furthermore, the LWC measured with FSSP2 was correlated with the LWC measured with the rotating cylinder, at subzero temperatures. The correlation equations were then used to estimate the LWC as measured by the rotating cylinder from the values obtained with FSSP2 in the linear range, at above zero temperature. The combined results (Figures 13 and 14) show that the temperature did not have a significant effect on the FMD response in the range from -5°C to +5°C. The results of the correlations, given in Table 4, indicate that the value of the slope for the present FMD design is bigger than that for the previous design. The present design is based on a laser source instead of a visible light source.

TABLE 2

FMD BASELINE AT EQUILIBRIUM

Temperature (°C)	Baseline FMD1 (V)	FMD2 (V)
1) Icing Wind Tunnel		
25.0	0.312	0.346
4.8	0.060	0.140
2.2	0.059	0.143
-2.3	0.029	0.103
-5.0	0.030	0.104
2) Cold Chamber		
14.5	0.173	0.225
11.0	0.131	0.211
0.0	0.062	0.148
-2.3	0.038	0.094
-8.2	0.025	0.087

3.3 Optical Cloud Detector

An Associated Weather Services OCD was tested in the wind tunnel. The OCD was placed diagonally across in order to fit into the tunnel. The LWC (as determined with the FSSP2) was noted when the LED on the photoelectric sensor of the OCD was on or off. The results are given in Table 5. The on/off point of the OCD at -5°C was about 0.06-0.07 g/m^3 at high sensitivity setting and about 0.12 g/m^3 at low sensitivity setting. The values at the high sensitivity setting are close to the values reported by the manufacturer (0.045-0.06 g/m^3).

TABLE 3

FMD CALIBRATION RESULTS, ICING WIND TUNNEL

Temp (°C)	Velocity (m/s)	FMD1 (V)	FMD2 (V)	LWC Rotating Cylinder (Front) (g/m³)	LWC Rotating Cylinder (Back) (g/m³)	LWC (FSSP) (g/m³)	MVD (FSSP) (μm)
-5	4.5	0.250	0.202			0.14	8.7
		0.358	0.300	0.14	0.12	0.22	9.5
		0.431	0.377	0.21	0.20	0.31	10.4
		0.546	0.459	0.27	0.25	0.39	11.3
		0.669	0.570	0.31	0.29	0.51	12.1
		0.719	0.614	0.35	0.33	0.56	12.5
		0.769	0.650	0.41	0.31	0.60	12.8
		1.084	0.893	0.53	0.45	0.82	15.0
-2.3	4.5	0.230	0.164	0.07	0.07	0.11	8.0
		0.370	0.308	0.17	0.17	0.22	9.2
		0.464	0.389	0.20	0.20	0.30	10.2
		0.576	0.495	0.25	0.26	0.39	11.0
		0.727	0.635	0.37	0.36	0.54	12.2
		0.801	0.695	0.43	0.35	0.60	12.5
		0.926	0.800	0.45	0.40	0.70	13.0
		1.017	0.894	0.60	0.50	0.83	14.7
		1.082	1.076	0.70	0.73	0.86	14.6
		1.091	1.028	0.72	0.51	0.80	14.4
		1.151	1.035	0.76	0.64	1.01	15.9
4.8	4.5	0.066	0.050	- 0.02	0.00	0.02	7.4
		0.218	0.196	0.03	0.05	0.09	8.1
		0.412	0.361	0.13	0.13	0.22	9.5
		0.643	0.565	0.26	0.24	0.38	10.8
		0.906	0.805	0.44	0.38	0.61	12.4
		1.131	1.006	0.60	0.52	0.82	13.9
		1.256	1.114	0.73	0.62	0.98	14.9
		1.550	1.385			1.45	17.5
		1.791	1.603			2.05	20.5
		1.968	1.822			3.45	27.1
		2.000	1.798			3.05	25.1
2.2	4.5	0.221	0.177	0.04	0.06	0.10	7.6
		0.377	0.314	0.12	0.12	0.20	8.6
		0.550	0.466	0.21	0.20	0.32	10.0
		0.664	0.568	0.27	0.25	0.40	10.8
		0.763	0.656	0.34	0.31	0.49	11.5
		0.910	0.786	0.44	0.38	0.61	12.4
		1.087	0.938	0.60	0.51	0.81	14.0
		1.254	1.095			1.02	15.3
		1.527	1.342			1.45	17.9
		1.758	1.557			2.00	20.7
4.8	2.5	0.221	0.183	0.04	0.06	0.10	8.3
		0.429	0.373	0.13	0.13	0.22	9.7
		0.761	0.691	0.33	0.29	0.47	11.0
		0.999	0.925	0.47	0.41	0.65	12.1
		1.142	1.053	0.59	0.51	0.80	13.5
		1.365	1.266	0.75	0.64	1.01	14.5
		1.707	1.616			1.39	16.1
		2.041	1.947			2.03	19.0
		2.313	2.260			2.90	22.5
		2.301	2.182			3.60	25.5

*Values estimated from the FSSP2's LWC at -5 and -2.3°C

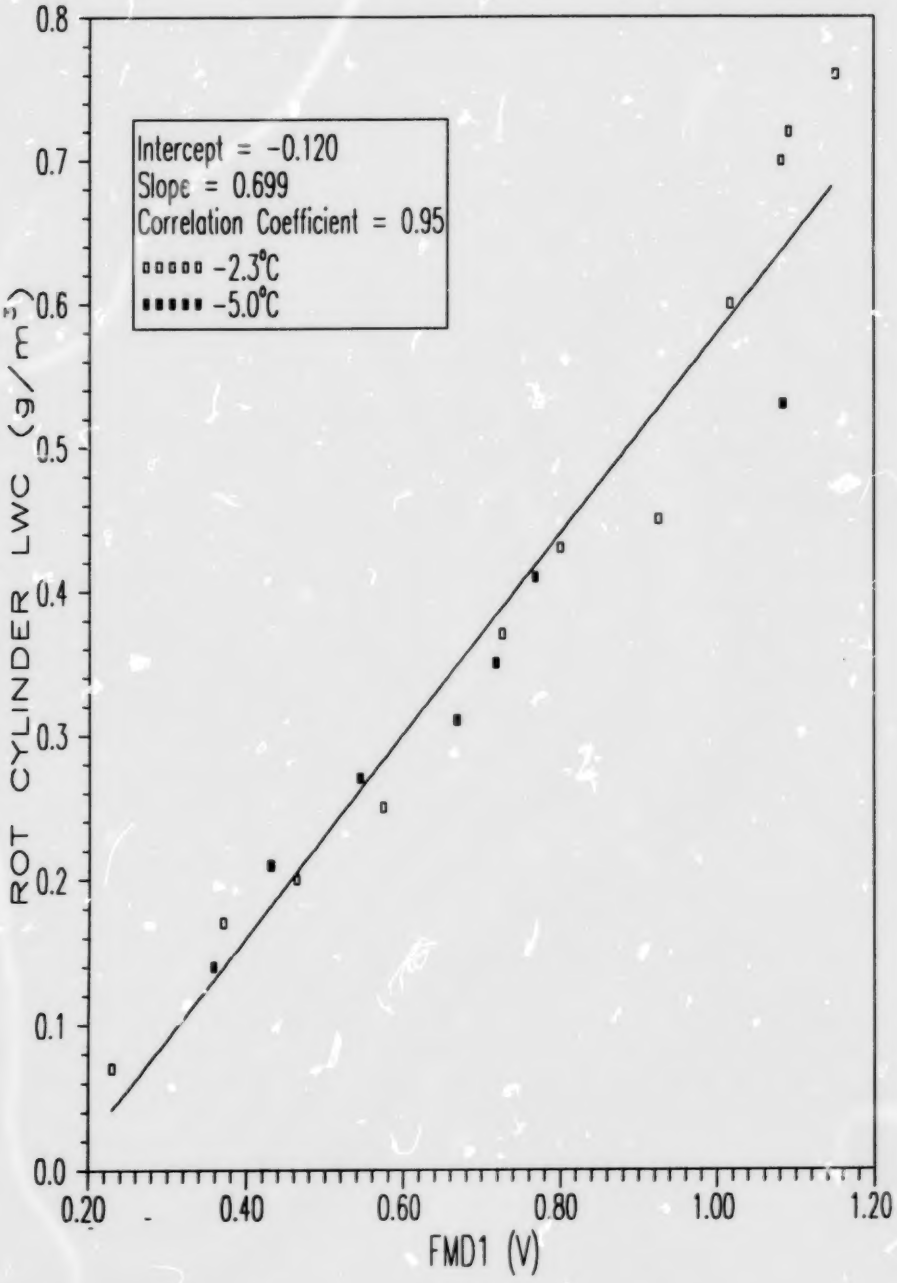

Figure 9 - FMD1 Calibration (NRC, Nov 1-2, 1989)

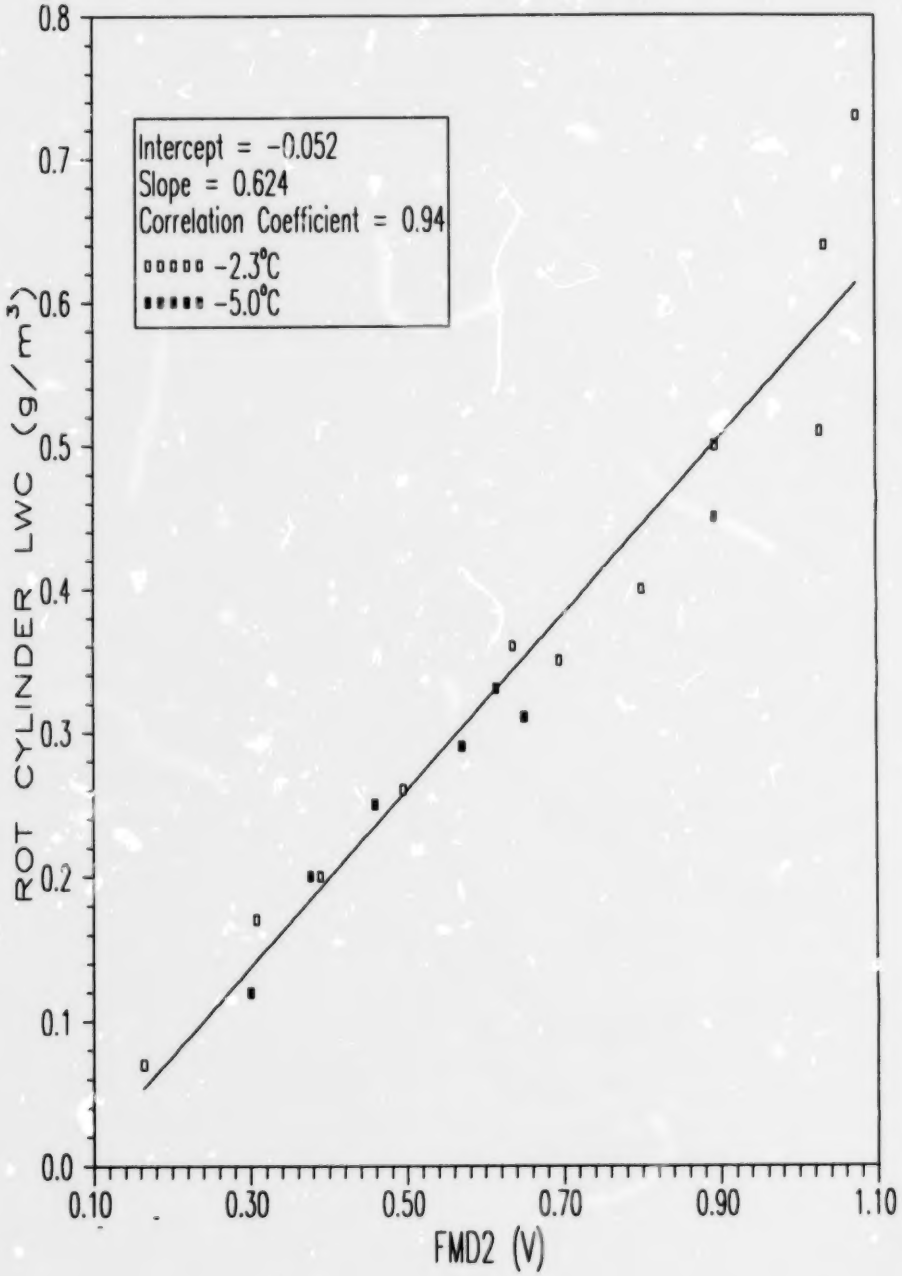

Figure 10 - FMD2 Calibration (NRC, Nov 1-2, 1989)

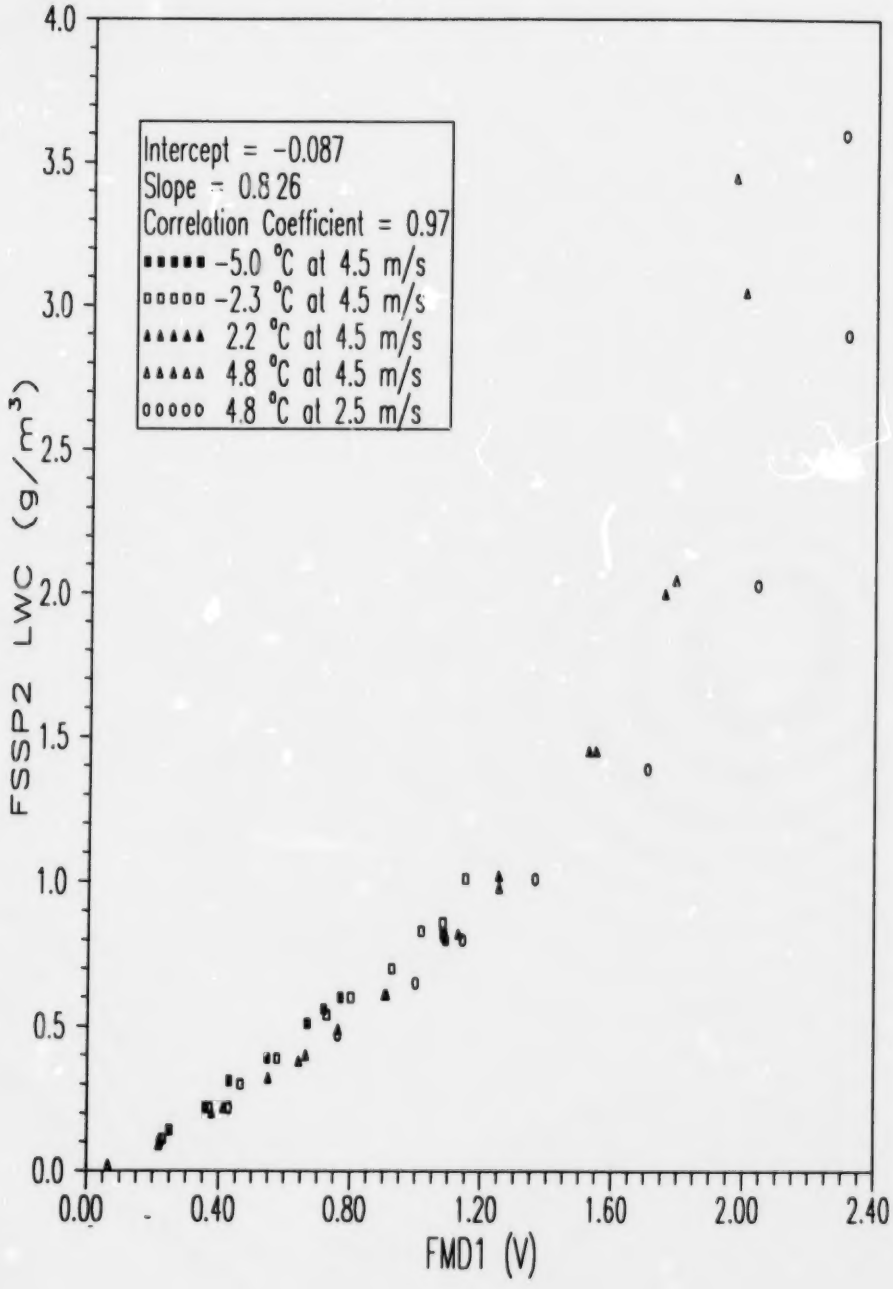

Figure 11 - FMD1 Calibration (NRC, Nov 1-2, 1989)

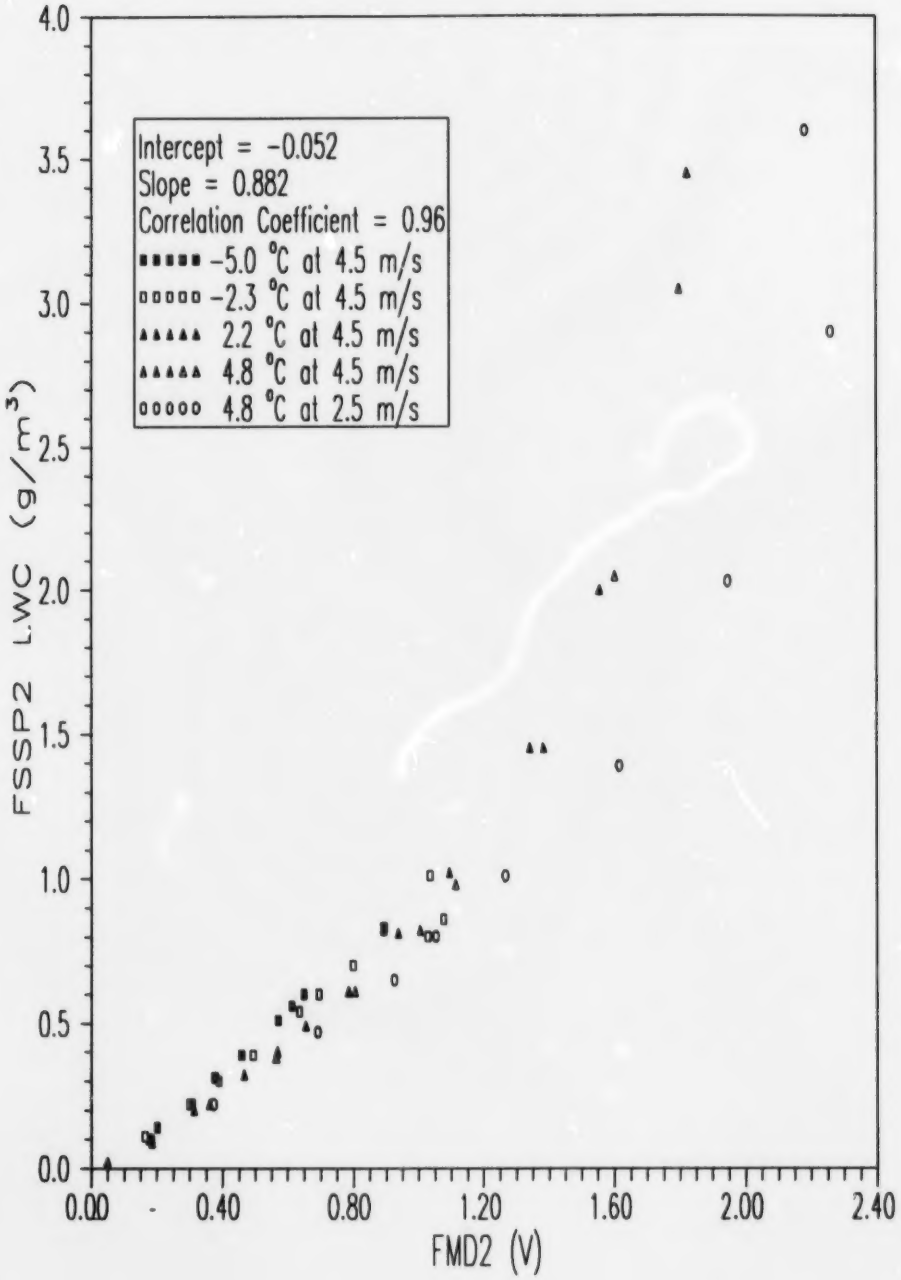

Figure 12 - FMD2 Calibration (NRC, Nov 1-2, 1989)

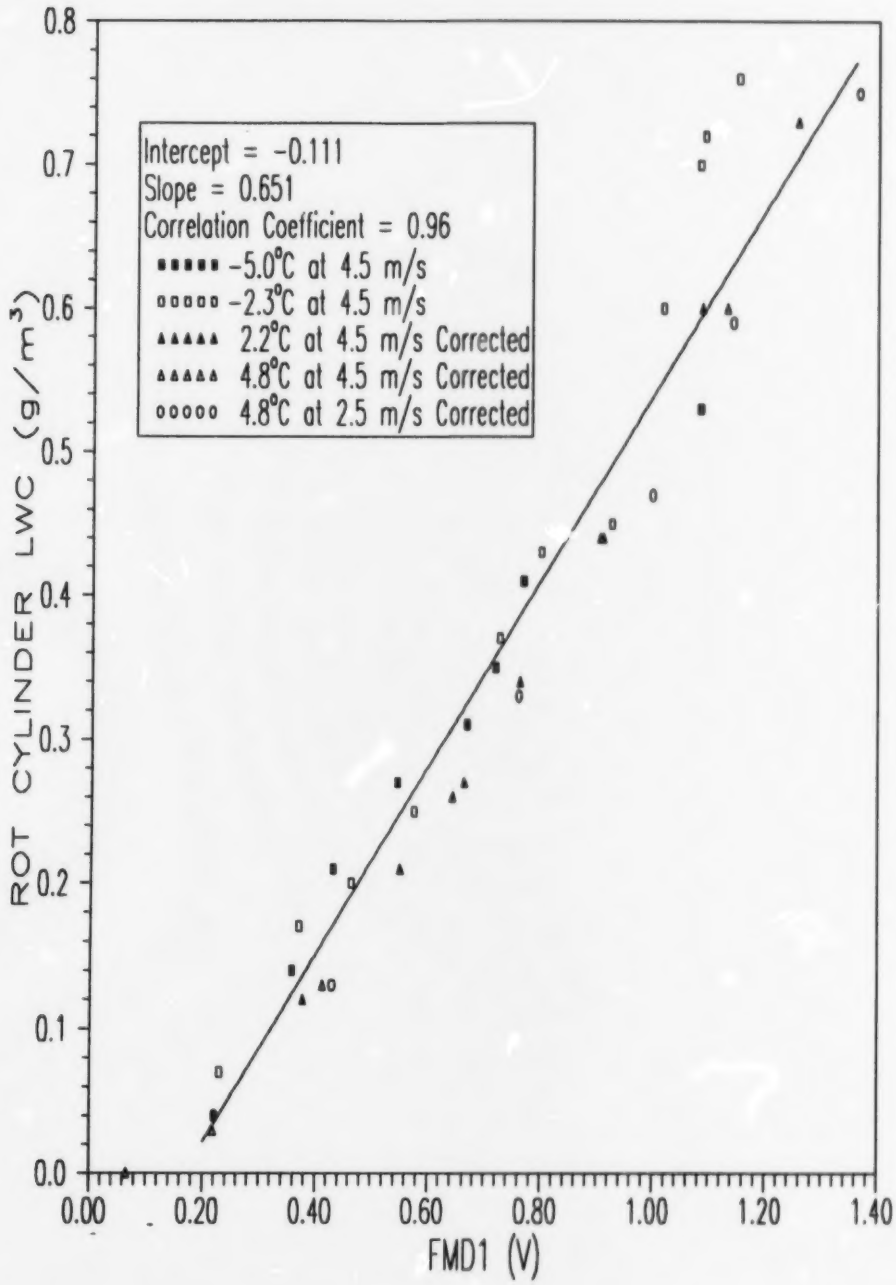

Figure 13 - FMD1 Calibration (NRC, Nov 1-2, 1989)

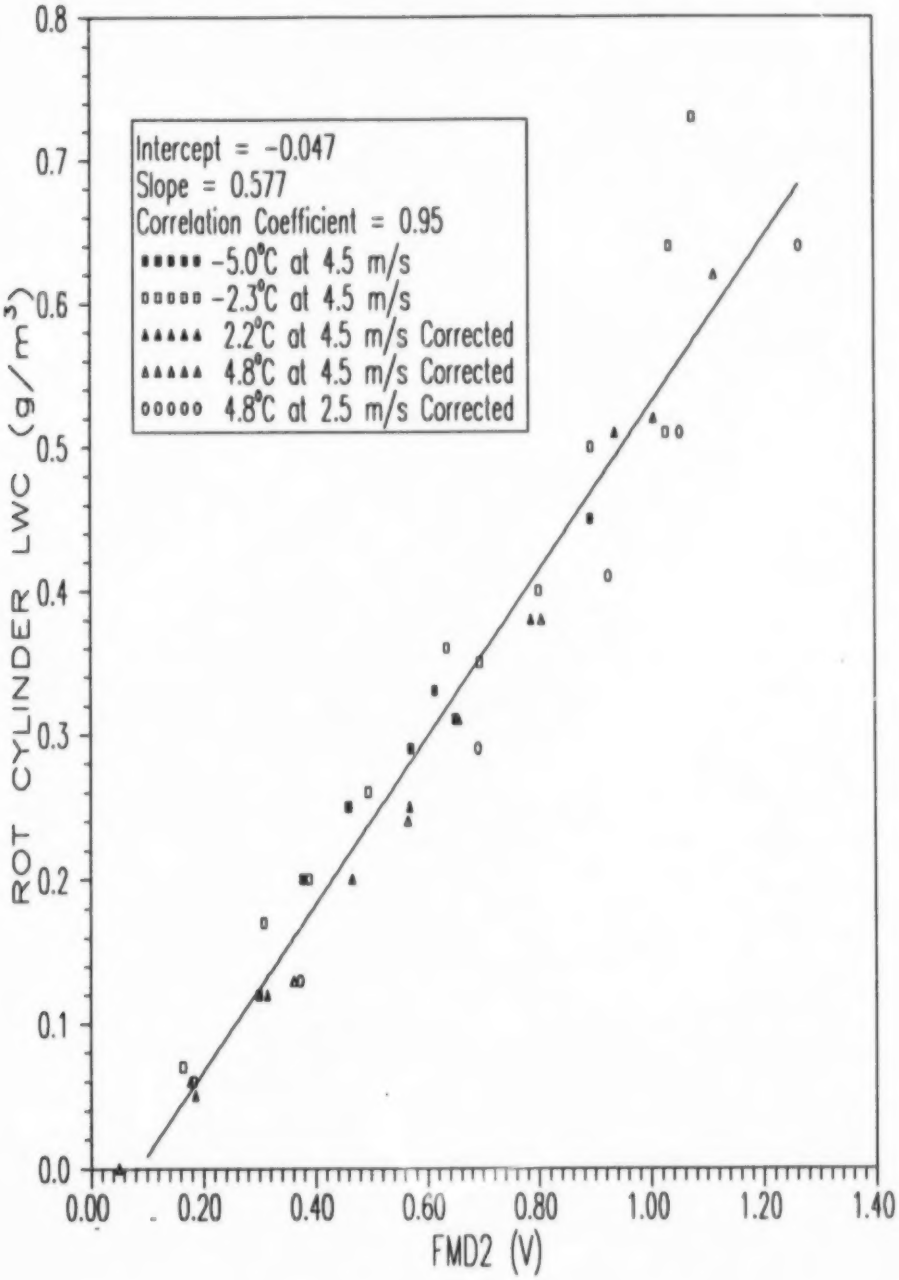

Figure 14 - FMD2 Calibration (NRC, Nov 1-2, 1989)

TABLE 4

FMD CORRELATION RESULTS IN THE FORM OF y = a+bx where a = intercept and b = slope

y (g/m^3)	x (V)	Intercept (g/m^3)	Slope ($g/m^3/V$)	Corr. Coeff.	Conditions
LWC	FMD1 Signal	-0.120	0.699	0.95	Rotating Cylinder
LWC	FMD2 Signal	-0.052	0.624	0.94	@ -5 and -2.3°C @ 4.5 m/s LWC up to 0.8 g/m^3
LWC	FMD1 Signal	-0.111	0.651	0.96	Rotating Cylinder
LWC	FMD2 Signal	-0.047	0.577	0.95	corrected from FSSP2 @ -5,-2.3, 2.2,4.8°C @ 2.5, 4.5 m/s LWC up to 0.8 g/m^3
LWC	FMD1 Signal	-0.087	0.826	0.97	FSSP2
LWC	FMD2 Signal	-0.052	0.882	0.96	@ -5, -2.3, 2.2, 4.8°C @ 2.5, 4.5 m/s LWC up to 1 g/m^3
LWC	FMD Signal	0.003	0.420		AES results on previous FMD design based on FSSP's LWC

TABLE 5

SENSITIVITY OF THE OPTICAL CLOUD DETECTOR, ICING WIND TUNNEL

Temp. (°C)	Velocity (m/s)	LED	Sensitivity Setting	FSSP2 LWC (g/m^3)	FSSP2 MVD (μm)
-5	4.5	off	High	0.02	12.2
		on	High	0.05	13.0
		off	High	0.01	5.9
		intermittent	High	0.06	7.9
		intermittent	High	0.08	7.9
		on	High	<0.10	8.0
-5	2.6	on	High	0.06	8.0
-5.2	2.6	off	LOW	0.03	8.2
		on	LOW	0.12	9.8

3.4 Velocity Meter

ESS's velocity meter (Testoterm Instant Action Anemometer, model 4510) was compared with NRC's Kurtz mini-anemometer and pitot tube in the wind tunnel at about -5°C. Velocity measurements were taken with the Testoterm meter and with the Kurtz meter sequentially at approximately the same location in the tunnel. On the other hand, the pitot tube measurements were made at other locations. The results are given in Table 6. The velocity measurements with the Testoterm meter correlated very well with those from the Kurtz meter (Figure 15). This gave us more confidence in using the Testoterm meter in the rotating cylinder measurement technique. On the other hand, correlation with the pitot tube (Table 6) was very poor due to two reasons: low sensitivity of the pitot tube and different sampling locations.

4.0 COLD CHAMBER TESTS

The FWC, FMD, FSSP2 and OCD were tested in the Cold Chamber (Figures 16 and 17). The size of the Cold Chamber is about 6.8 m long, 3.5 m wide and 2.6 m high. The temperature inside the chamber can be varied from about -38°C to about +50°C. The droplets were generated by means of a spraying bar consisting of four nozzles, and were dispersed by means of two fans located behind the nozzles. The fog detection and sampling equipment was placed at the other end of the chamber facing the nozzles. The FSSP2 was placed side by side with the fog water collector. The two FMDs and the OCD were put on top of the fog water collector. The exhaust from the fog water collector was redirected away from the equipment to minimize any disturbance to the other equipment. The temperature inside the chamber was kept at about 8 ± 3°C, and at about -4 ± -2°C. (Please note that the temperature inside the chamber increased slowly with time.)

4.1 Fog Water Collector

Before the test, the velocity profile inside the FWC was measured by means of the Testoterm meter. The meter was inserted into one of the three holes aligned vertically on one side of the collector. Two sets of three holes were made in the front and at the back of the screens. The measured profile is given in Table 7. The fog-laden air appeared to be deflected from the inlet hood and directed at the top part of the collector. The flow pattern after the screens was more uniform.

TABLE 6

COMPARISON OF VELOCITY METRES IN THE ICING WIND TUNNEL

Velocity (m/s) @ -5.1°C		
Testoterm	Kurtz	Pitot Tube
0.00	0.56	0.00
1.70	1.52	0.00
2.59	2.79	0.00
3.69	3.66	0.00
4.39	4.22	2.14
5.59	5.46	3.77
6.52	6.35	4.87
7.67	7.62	6.37
8.43	8.38	7.35
9.12	9.02	8.11
9.78	9.91	8.89

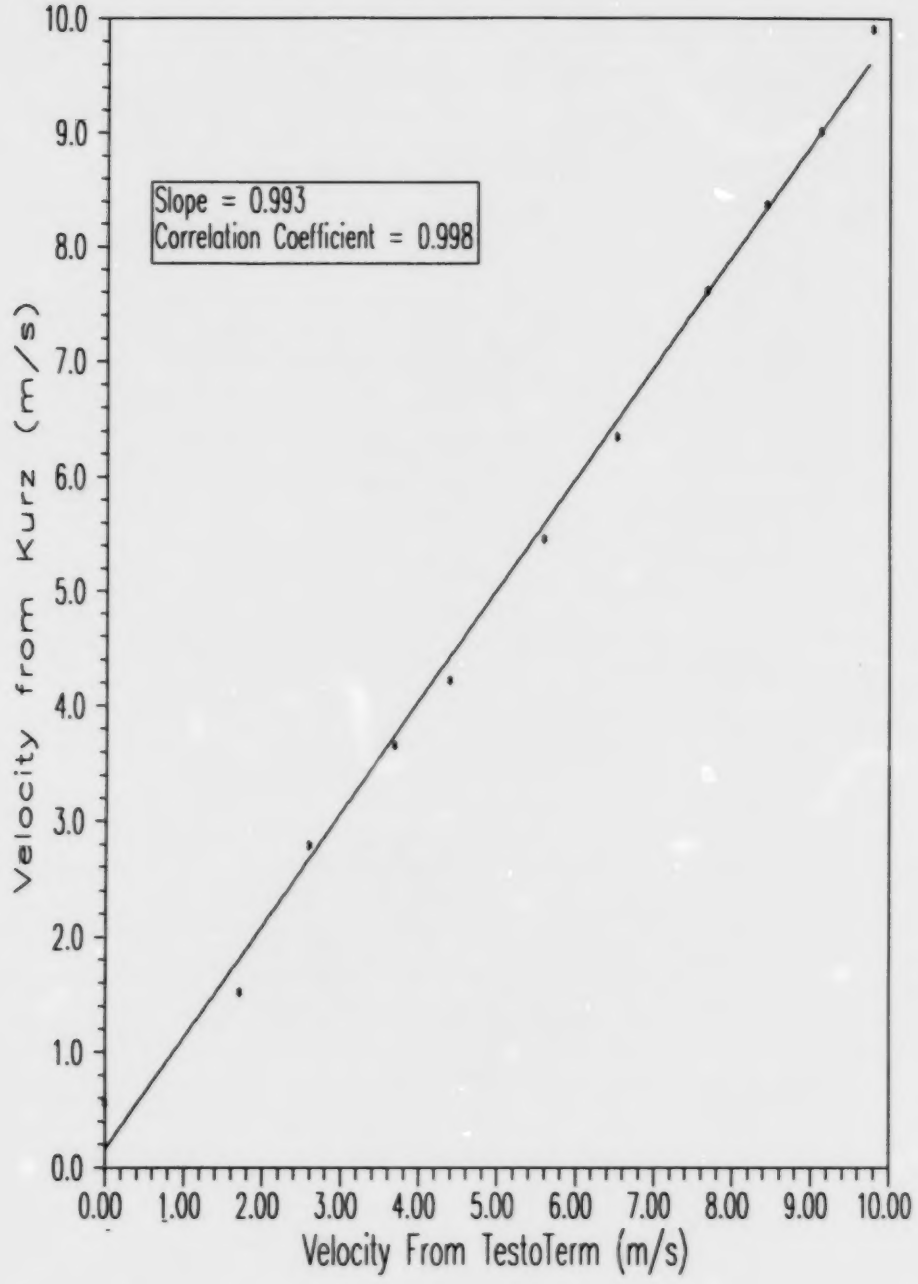

Figure 15 - Velocity Comparison, (NRC, Nov 2, 1989)

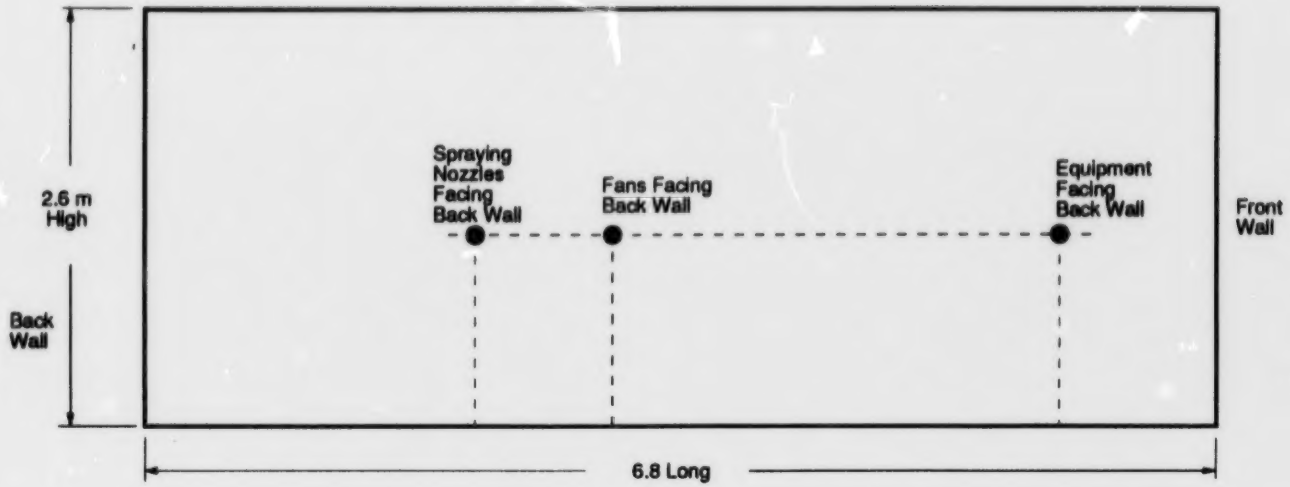

FIGURE 16

COLD CHAMBER SET-UP

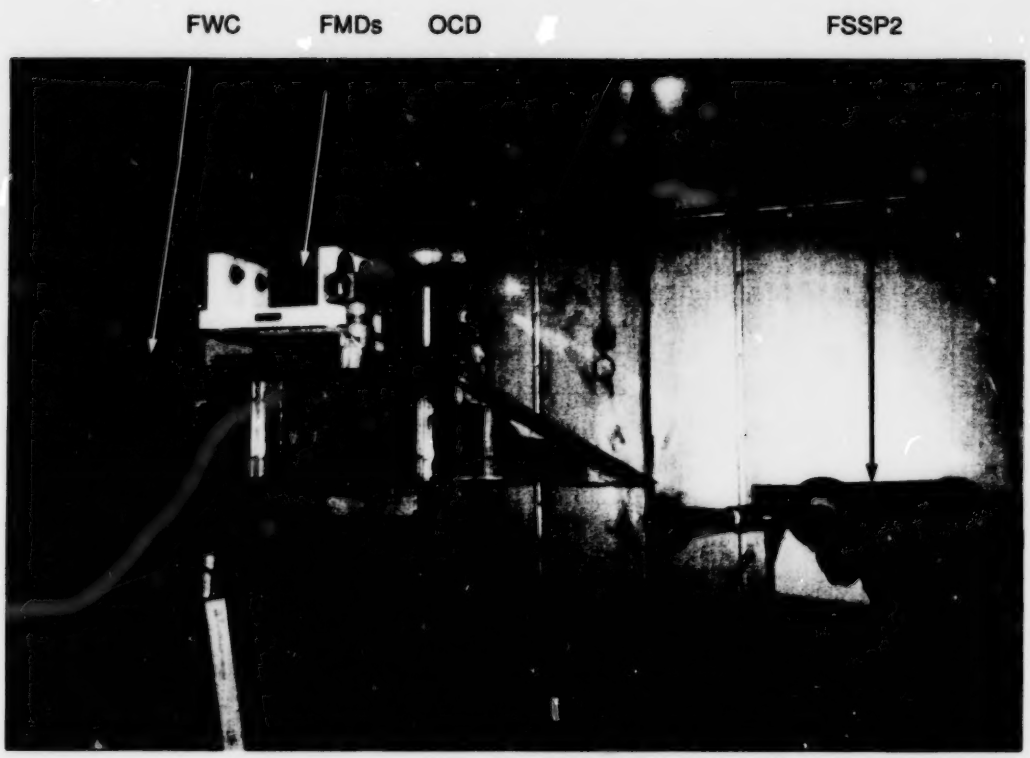

FIGURE 17

EQUIPMENT SETUP IN THE COLD CHAMBER

TABLE 7

VELOCITY PROFILE INSIDE THE FOG WATER COLLECTOR

		Velocity (m/s) 1	2	3	Average
1) **Before the test**					
Front Holes	Top	8.4	8.6	8.3	8.4
	Middle	8.5	8.6	9.0	8.7
	Bottom	4.4	3.0	5.4	4.2
Back Holes	Top	6.3	6.6	6.5	6.5
	Middle	6.7	7.5	7.4	7.2
	Bottom	7.5	7.0	8.0	7.5
2) **During the test** (ice on the screens)					
Front Holes	Top	8.7	7.0	7.8	7.8
	Middle	9.5	9.0	8.5	9.0
	Bottom	2.8	2.5	2.5	2.6

The efficiency of the collector was measured at two temperatures (8 ± 3°C, -4 ± -2°C). The collection efficiency is defined in this study as the ratio of the amount of fog water collected in the sample bottle to the value determined by the product of the ambient LWC and the sample flow volume. The sample flow rate was about 27 m^3/min. The ambient LWC was determined by the average value reported by the FSSP2, FMD1 and FMD2 values corrected to the rotating cylinder's LWC according to Section 3.2. Two screens were used in all tests, except Run 8. In this case, three screens were used. The results are given in Table 8. The results should be taken as qualitative values due to uncertainties in measuring the ambient LWC and to the non-uniformity and fluctuations of the LWC inside the chamber. Despite this difficulty, the results indicated that the efficiency of the collector was very high (above 80%) at above zero temperature, close to the expected value of about 90%. The efficiency above 100% was questionable and may be due to the mentioned uncertainties in the ambient LWC.

On the hand, under subzero temperature, most of the fog droplets froze upon impact on the screens (rime ice), and in most cases, the deposits were blown off the screens. The ice-laden screens increased the flow resistance and hence the flow rate decreased slightly as indicated by the drop in velocity in front of the screens (Table 7). The collected fog sample was determined by defrosting the screens and weighting the liquid. The collection efficiency was very low (around 20%) probably due to the loss of deposits and to the slight decrease in sampling rate.

4.2 Fog Water Collection and Detection Equipment

The FMDs, the FSSP2 and the OFD were tested inside the Cold Chamber. The equipment behaved similarly as in the Icing Wind Tunnel. The sensitivity of the OFD at the high sensitivity setting was about 0.05 g/m^3, as determined by the FSSP2. The FMD1 and FMD2 signals were corrected to LWC according to the correlations in Table 4. The corrected LWC as determined with the FMDs is compared with the FSSP2 readings in Figures 18 and 19. The correlations were good.

TABLE 8

COLLECTION EFFICIENCY OF FOG WATER COLLECTOR (flow rate = 27 m^3/min)

Run	Time (min)	MVD (μm)	Temp (°C)	Fog Sample (g)	Average LWC (g/m^3)	Efficiency (%)
1	10	15.4	5	263.68	0.81	120
2	10	15.4	6.2	280.53	0.92	113
3	10	13.6	8.1	188.89	0.70	100
4	10	11.5	9.4	75.34	0.35	80
5	21	10.3	10.6	76.48	0.15	89
6	20	20.0	-1.6	88.37	0.19	85
7	30	9.0	-3.1	7.26[1] 7.34[2]	0.08	23
8	15	13.0	-2.4	6.72[1] 11.77[2] 9.21[3]	0.41	17

[1] 1st screen
[2] 2nd screen
[3] 3rd screen

5.0 CONCLUSIONS

The Forward Scattering Spectrometer Probe (FSSP1), the two Fog Measuring Devices (FMD) and the Optical Cloud Detector (OCD) were tested in the National Research Council's Icing Wind Tunnel, and Cold Chamber. Despite the limited data set, it can be concluded that the LWC measured by the FSSP1 correlated well with the rotating cylinder method. The FSSP1, corrected for coincidence/dead time loss, underestimated the LWC by about 30% when compared with the rotating cylinder. The FMDs were found to be very sensitive to LWC. The FMD output, corrected for the baseline drift, increased linearly with the LWC determined with the rotating cylinder, up to about 0.8 g/m^3. Similarly, the FMD output increased linearly with the LWC determined with the FSSP2, up to about 1.0 g/m^3 and became saturated at about 2 g/m^3. It was observed that temperature had no significant effect on the response of the FMD (corrected for the baseline drift) over the temperature range of -5 to +5°C, and had an effect on the baseline of the FMD output. The temperature effect on the baseline needs to be investigated further. Furthermore, the effect of velocity on FMD response was unclear. Velocity had no significant effect on the FMD response up to about 1 g/m^3. But, at saturation, the FMD signals seemed to depend on velocity. The on/off point of the OCD was about 0.05-0.07 g/m^3 at the high sensitivity setting and about 0.12 g/m^3 at the low sensitivity setting.

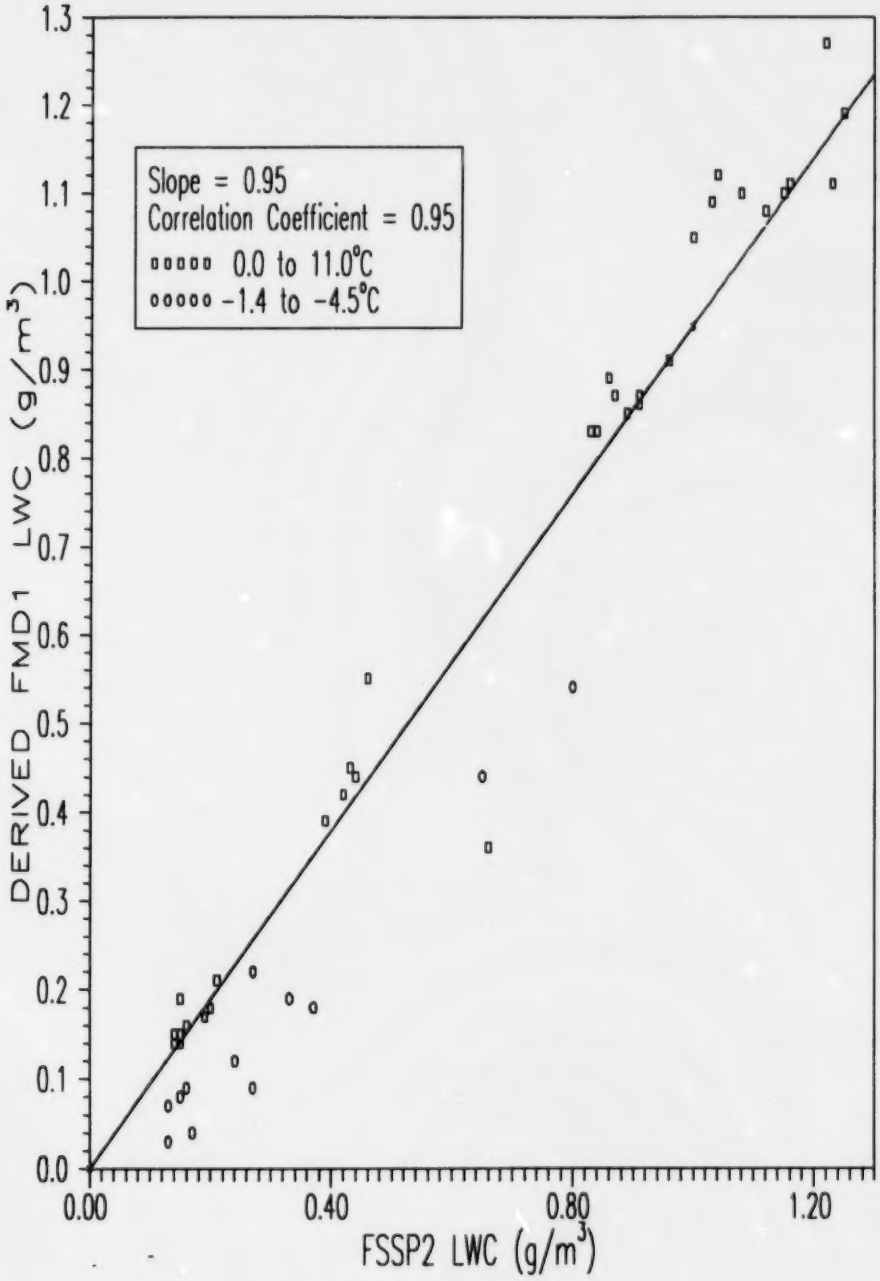

Figure 18 - FMD1 Testing in the Cold Chamber

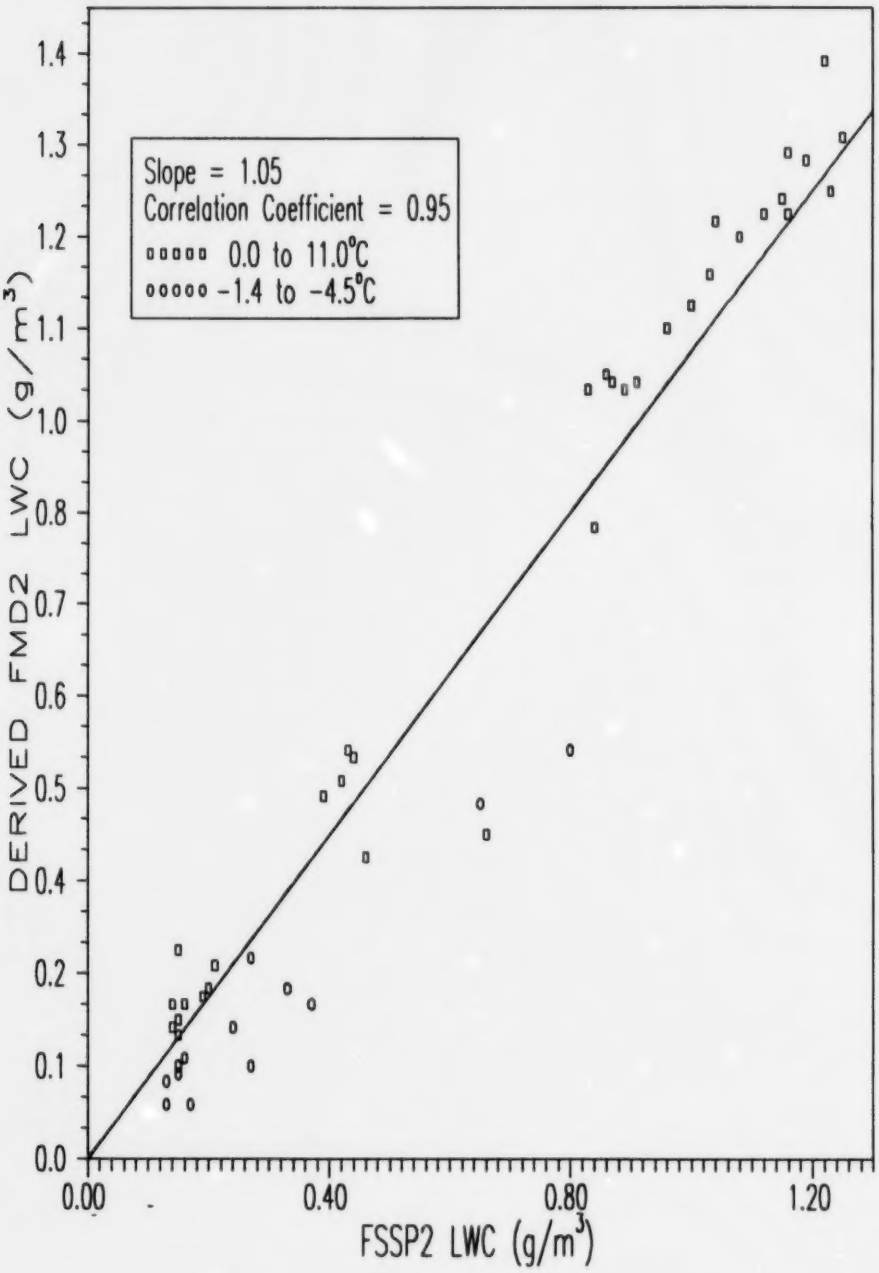

Figure 19 - FMD2 Testing in the Cold Chamber

The performance of the Fog Water Collector was tested in the Cold Chamber. The results indicated that the collection efficiency was very high (> about 80%) at above zero temperature, and was very low (about 20%) under subzero temperature.

6.0 RECOMMENDATIONS

On the basis of the experience/knowledge gained during the NRC study, a number of recommendations are provided below.

i) It is convenient and also efficient if a real time display of droplet size and liquid water content, along with the size spectrum, can be incorporated into the software for the Forward Scattering Spectrometer Probe. This information is important in the calibration work in assessing the conditions within the tunnel, quickly, so that an appropriate action can be taken. It is recommended that the source code for the FSSP be modified to incorporate this change. A Print Screen software (Grafplus from Jewell Technologies) could be used to download the information off the screen to the printer if needed. (A commercial real time software package for the FSSP is quite expensive, about US $12,000).

ii) The FMDs are extremely sensitive to LWC and hence suitable for low LWC measurements (such as ambient fog monitoring). However, the effect of temperature on the baseline should be investigated further, particularly for those applications that involve wide temperature ranges. The temperature range for the Insulator Icing Study is quite narrow (from about -5°C to + 5°C). For this case, the problem may not be serious.

iii) The Optical Cloud Detector should be set at the high sensitivity level. This setting will allow the detector to turn on the Fog Water Collector at about 0.05-0.07 g/m^3 LWC.

iv) The Fog Water Collector is suitable for above zero temperature applications. For subzero temperature application, the collector should be modified. The collection screens should be heated slightly above 0°C to enhance fog water collection. Furthermore, the collector should be equipped with an automatic cover to minimize contamination when there is no fog.

v) The FSSP, the FMD and the OCD could be calibrated using NRC's Icing Wind Tunnel. For future calibration, the uniformity of LWC across the tunnel should be checked first by observing the pattern of ice deposited on the black painted grid across the tunnel. The Cold Chamber is not quite suitable to calibrate the Fog Water Collector since the temperature inside the Cold Chamber cannot be maintained at a fixed value for a period of over an hour.

vi) The rotating cylinder technique is used to measure LWC under sub-zero temperatures. The possibility of using the rotating cylinder technique at above zero temperatures is worth investigating. We could cool the rotating cylinder by means of a thermoelectric cooler.

Approved by:

for D.J.R. Dodd
Manager
Chemical Research Department

Prepared by:

H. Leung
Engineer
Environmental Science Section

Reviewed by:

O.T. Melo
Supervising Engineer
Environmental Science Section

REFERENCES

(1) Stallabrass, J.R. (1978). "An Appraisal of the Single Rotating Cylinder Method of Liquid Water Content Measurement". NRC report LTR-LT-92.

(2) Baumgardner, D., W. Strapp and J.R. Dye (1985). "Evaluation of the Forward Scattering Spectrometer Probe. Part II. Corrections for Coincidence and Dead-time Losses". J. Atm. and Oceanic Technol., **2**, 626-632.

(3) Baumgardner, D. (1983). "An Analysis and Comparison of Five Water Droplet Measuring Instruments". J. Climate Appl. Meteor., **22**, 891-910.

(4) Lemyk, A. and G.L., Ogram (1990). "The Forward Scattering Spectrometer Probe". Ontario Hydro Research Report 89-297-K

(5) Gerber,H. (1984). "Liquid Water Content of Fogs and Hazes from Visible Light Scattering". J. Climate Appl. Meteor., **23**, 1247-1252.

(6) Jacob,D.J., J.M. Waldman, M. Haghi, M.R. Hoffmann and R.C. Flagan (1985). "Instrument to Collect Fogwater for Chemical Analysis". Rev. Sci. Instrum., **56**, 1291-1293.